Development of Grid Protection Relays for Off-Grid Power Network Mostly Using Inverter-Based Power Source

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Abstract

Off-grid power supply is mainly performed by diesel generators. In the off-grid power system world, it is expected to expand the introduction of Renewable Energy (RE) resources from reducing operating fuel costs and controlling CO_2 emissions.

Most of the RE resources, however, are inverter-based power sources. If these become the main power sources, reducing the fault current in the event of a short circuit will be a challenge. For this reason, Tokyo Electric Power Company Holdings, Inc. and Meidensha Corporation have developed a new protection relay unit that applies short-circuit protection measures to off-grid power supply system. Such systems use the RE resources which are the inverter-based power supply. This protection relay unit also considers replacing conventional off-grid distribution line protection. A real-time simulator was used to evaluate the prototype unit under various system conditions, and favorable results were obtained.

1 Preface

Currently, off-grid power is supplied mainly by diesel generators, which incur fuel and transportation costs off-grid efforts, however, are underway to expand the introduction of Renewable Energy (RE) resources. By applying RE resources such as Photovoltaic (PV) power generation and Battery Energy Storage Systems (BESS) to off-grid systems, it is expected that fuel costs for diesel generators and CO_2 emissions will be reduced.

Until now, it has been widely studied that the reduced inertial force of grids due to the increased introduction ratio of inverter power sources, such as PV power generation and BESS, affects frequency fluctuation[(1)]. On the other hand, there have been no published examples of concrete investigations of the effects on system protection and countermeasures against the reduction in short-circuit current during short-circuit faults. Tokyo Electric Power Company Holdings, Inc. and Meidensha Corporation, therefore, have been evaluating the impact on system protection and are considering countermeasures when inverter power supplies, such as PV power generation and BESS become the main power source in off-grid power supply systems[(2)(3)].

This paper introduces the results of developing, prototyping, and evaluating a relay unit. This relay unit incorporates the countermeasures that have been studied so far.

2 Specifications of Developed Relay Unit

2.1 Relay Sequence

When a line-to-line short-circuit fault occurs in the off-grid condition, where the inverter-based power supply is the main power source (voltage source), the inverter adjusts the output voltage so that the current it supplies is not exceeded. This reduces the line-to-line voltage of the fault phase and reduces the short-circuit current compared to when the diesel generator is the main power source[(2)~(5)]. Based on these findings, we assumed off-grid power supply using 6 kV and 3 kV high-voltage distribution lines, and studied a method that can detect short circuits and select faulty lines even if the short-circuit current decreases[(6)]. In doing so,

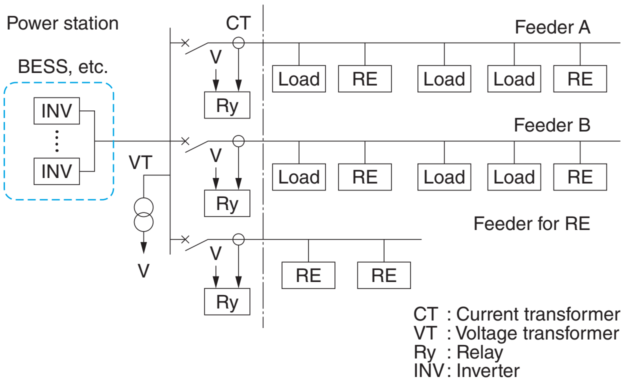

Fig. 1 **Example of OFF-Grid System Configuration**

An example of predicted off-grid system configuration is shown.

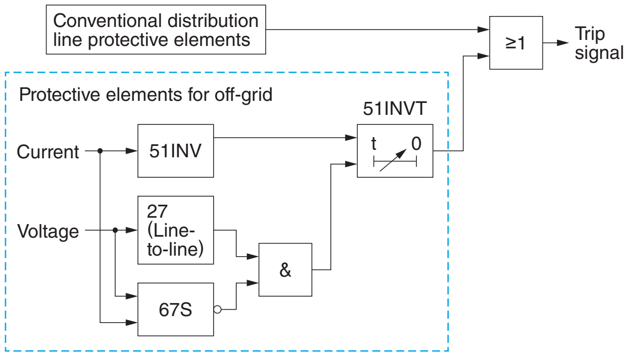

Fig. 2 **Off-Grid Protection Sequence (Outlined)**

An additional sequence for short-circuit fault protection is shown, needed when inverters are used for the main power source of off-grid.

the following elements were added to the existing distribution line protection elements. We considered the need to prevent unnecessary trips on healthy lines connected to a large amount of RE resources, as well as unnecessary trips on other healthy lines.

(1) 51INV

It detects that the distribution line current to be protected exceeds the value assumed to be the overload condition of the inverter power supply.

(2) 27 (line-to-line)

It detects a drop in the line-to-line voltage of the bus.

(3) 51INVT

In order to avoid unnecessary trips on healthy lines, it has an inverse time-delay characteristic that adjusts the operating time according to the magnitude of the distribution line current to be protected.

(4) 67S

It detects the power flow direction of protected distribution lines in order to avoid unnecessary trips on healthy lines that are interconnected with a large amount of RE resources.

Fig. 1 shows an example of an off-grid system configuration, and **Fig. 2** shows a protection sequence combining the considered elements.

2.2 Relay Unit

Our relays, which are currently used to protect off-grid distribution lines, are unit-type relays that can be mounted on switchgears. The hardware (MRC series) developed in the early 1990s has already been discontinued and only its maintenance and repair is available. We, therefore, developed a relay unit that combines the existing unit-type hardware MRR series with conventional protection elements and new elements for off-grid use. **Fig. 3** shows the developed relay unit, and **Table 1** shows a comparison of main specifications with the conventional unit. In terms of the Central Processing Unit (CPU) performance, program rewrite ability, analog performance, and reliability, the hardware is upwardly compatible with conventional units. Considering the need to update existing units, the installation dimensions for the switchgear are also compatible.

Fig. 3 **Developed Relay Unit**

An external appearance of the developed relay unit is shown.

3 Evaluation of Development Relays

3.1 Real-Time Simulation Model

For the developed relay unit, we first conducted a unit test based on the applicable standards, and confirmed that it was manufactured according to the design. It is difficult, however, to perform evaluations including responses to short-circuit faults of BESS and RE resources in off-grid using a general relay tester. Therefore, this time, we used a real-

Table 1 Comparison of Relay Specifications (Excerpt)

Compared with conventional models, the newly developed equipment is based on upward compatible specifications. The external dimensions are devised with due consideration to the replacement of the relay unit.

Item	Conventional model (MRC Series)	Developed model (MRR Series)
Applicable standard	Electric Power Standard B402, JEC-2500	
CPU (bits)	16	32
Program memory	EPROM (Socket replacement)	Flash memory
Analog sampling frequency (System frequency 50 Hz) (Hz)	600	4800
A/D converter resolution (bits)	12	16
Relay trip system	AI channel and output duplex	Totally duplex from AI to output section
Relay elements (Main protection)	51, 51t (Inversed definite time), 51T (Definite time), 51G, 67G, 67GT, 79	In addition to the left: 51INV, 51INVT, 27, 67S
External dimensions (mm)	W310 × H265 × D255	W310 × H260 × D240 + α
Mass (kg)	Approx. 15	Approx. 8

time simulator (HYPERSIM) for evaluation. An off-grid power network model including BESS and RE resources shown in Fig. 1 was built inside HYPERSIM, and analog quantities such as voltage and current and digital information such as the on/off status of circuit breakers were output in real time.

The relay received such information as input. Relay calculations were performed, trip signals were output, and HYPERSIM received these signals and changed the state of the circuit breaker. It also recorded the time series data of the power network model.

As an off-grid power network, the configuration shown in Fig. 1 was modeled. A BESS was connected to the power station busbar. In this system, this BESS was the main power supply (=voltage source), but when an overcurrent occurred, the voltage was adjusted to continue operation. A function was added to suppress the current to a functional level(7). Two feeders, A and B, were installed as normal distribution lines. The length and type of these distribution lines, as well as the capacity of the connected load and RE, were variable. The load was distributed with equal capacity near the power station, in the middle, and at the end of each distribution line. The RE resource was placed at two locations: near the power station and the end. A separate feeder dedicated to RE resources (variable output) was also installed. These RE resources were operated to supply the current just before the voltage drop in consideration of the continuity of operation in the event of a fault when the grid voltage drops. Fault points were also selected at various points such as the middle and end of each feeder and we evaluated.

3.2 Evaluation Results

Fig. 4 shows an example of real-time simulation waveforms. The system conditions in the simulation are that RE power generation is 600 kW from the feeder dedicated to RE. The total load is 600 kW in feeders A and B, and the length of the distribution line is short. On the assumption that a line-to-line fault is caused at the middle point of Feeder A at 0.2 seconds, the Fig. 4 shows: (a) power plant 3.3 kV bus phase voltages, (b) bus line-to-line voltage effective values, (c) Feeder A currents, (d) Feeder A current effective values, and (e) Feeder A relay signals (27 operation and trip signal). After the fault occurs, the line-to-line voltage between the fault phases drops to approximately 380 V, although the rated voltage is 3.3 kV (Fig. 4 (b)). In addition, the current of the Feeder A fault phase increases from about 100 A to a maximum of 238 A, and stabilizes at about 210 A (Fig. 4 (d)). Since 51INV was activated before the fault and 67S was not activated, the trip command was output from the relay after the activation time limit of 51INVT had elapsed, after 27 was activated after the fault (Fig. 4 (e)). In this case, a trip command was output from the relay 85 ms after the fault occurred, and the Feeder A circuit breaker opened after 3 cycles (60 ms). After that, the power station bus voltage returned to the rated level. We confirmed that the fault was eliminated. Also, we confirmed that relays, other than Feeder A, did not operate. The operation time limit of 51INVT could be adjusted by the operation setting value of 51INV and the time limit multiplier (N) of 51INVT. We can, therefore, make timed coordination with short-circuit protection at high voltage customer premises.

In addition to this example, we conducted the evaluation by various parameter combinations. As a result of the evaluation, it was confirmed that only the circuit breaker of the faulty feeder was opened and the fault was eliminated.

We then confirmed that the newly developed

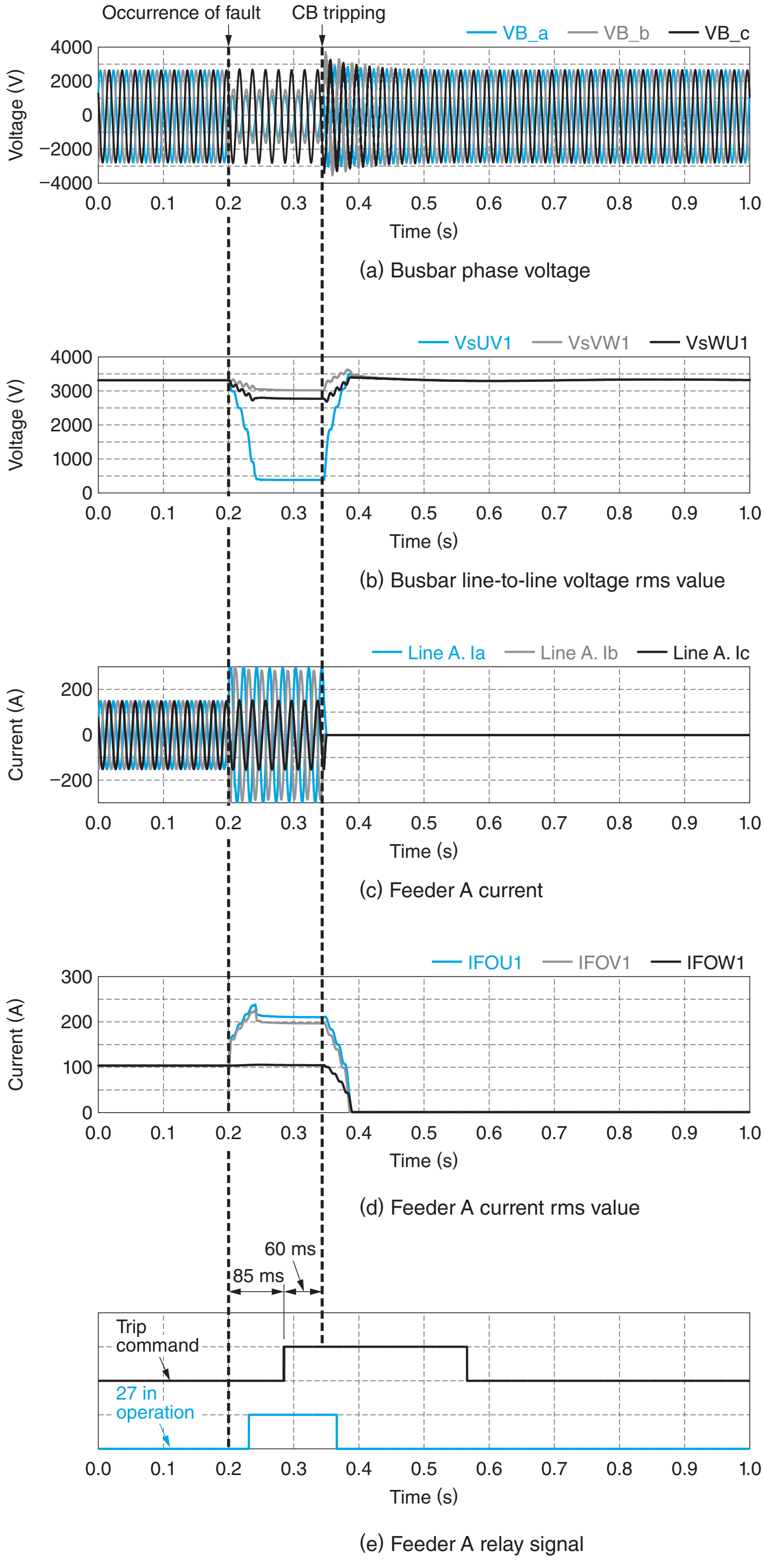

Fig. 4 **Example of Real-Time Simulation Waveforms**

Waveforms after the occurrence of a short-circuit fault are shown, from the lowering of line-to-line voltage detected by the relay, to the removal of the fault by tripping the circuit breaker.

relay can detect and protect against short-circuit faults in power distribution systems that are generally assumed to be off-grid. Since the high-voltage distribution system is ungrounded and the inverter is connected to the system via an insulated transformer, it is believed that conventional distribution line protection can be applied to prevent ground faults.

4 Postscript

We developed a protection relay unit that realizes the methods we have studied for short-circuit protection that responds to the reduction of fault current when inverters are used as the main power source. Such protection is an issue in realizing the expansion of RE introduction off-grid. The developed relay is upwardly compatible with conventional off-grid power distribution line protection, and the replacement of existing units is also considered. The operation of the prototype relay unit was evaluated by constructing an off-grid system model including RE in a real-time simulator. As a result, it was confirmed that even if the short-circuit current decreases due to the use of inverters as the main power supply in a distribution system that is generally assumed to be off-grid, short-circuit detection and failure line selection are possible.

In the future, as one of the components that will contribute to the expansion of the introduction of off-grid RE resources, we will proceed with studies and adjustments for on-site application.

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